CHAPTER I

INFRARED MEASUREMENTS OF SOUND SOURCE INTENSITIES IN JETS

by

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SUMMARY

Direct measurements of local sound source intensities in turbulent jets are being attempted using an optical cross-correlation technique. It has been shown that optical cross-beam measurements can be related directly to the volume integral describing the source strength. This paper represents a study of this relationship. The application and limitations of the technique are discussed in detail, with reference to Lighthill's and, in particular, Ribner's mathematical formulations. The latter formulation is particularly suited to cross-beam measurements since it expresses source strengths in terms of volume integrals of mass density fluctuations. Area integrals of density fluctuations are being attempted using a new infrared cross-beam system. Progress to date on subsonic jets with this system shows promise of giving the desired density dependence. Measurements were made using the CO_2 absorption band at 4.3μ. This type of measurement should be applicable to estimations of Mach-wave emission.

NOMENCLATURE

Symbol	Definition
$\vec{x}_f$	position vector $(x_f; y_f; z_f)$
$\vec{x}$	position vector $(x; y; z)$
$\vec{\xi}$	vector in direction of far-field observer $(\xi_1; \xi_2; \xi_3)$

$\vec{\xi}$	vector in direction of flow (ξ, η, ζ)
$\bar{\rho}$	mean density
ρ	fluctuating density
m_f	fluctuating mass fraction
k	absorption
$\bar{P}$	mean pressure
P	fluctuating pressure
$\vec{\bar{u}}$	mean velocity vector $(\bar{u};\ \bar{v};\ \bar{w})$
a_o	ambient speed of sound
a	local speed of sound
i	fluctuating signal
I	mean signal
ℓ	path angle
τ	retarded time
U_c	turbulence convection speed

Subscripts

A, B	radiation beams of the crossed-beam system
a	contribution from absorption
s	contribution from scattering

I-1. INTRODUCTION

The mathematical formulation of the jet noise problem [I-1,-2] has given us considerable insight into scaling laws associated with noise production, but little progress has been made in experimental verification of the predicted sound source strengths. The actual sound source

intensities as predicted by the theory are given in terms of turbulence flow properties which are extremely difficult to measure and even then must be incorporated into a complicated volume integral expression involving retarded time differences between statistical variables. Some attempts [I-3,-4], with a measure of success, have been made in estimating sound source strengths from hot wire measurements in low speed jet flows where the transformation to a moving frame of reference allows retarded times to be ignored to a good degree of approximation. At high speeds, this approximation is invalid; in fact, a singularity occurring at the sonic convection condition results in a prediction of infinite acoustic power radiated. A different type of noise source then dominates, and sound radiates from the jet in a manner analogous to Mach wave propagation [I-5].

An instrumentation technique, called the crossed-beam correlation method, has been recently developed [I-6] which automatically performs an area-integral of pertinent turbulent properties. This technique is similar in form to that required for a direct estimate of sound source intensity [I-7], and thus affords us the opportunity of measuring a part of the sound source volume integral directly. This paper covers the application of the technique to the Mach wave emission expected from supersonic jets and discusses progress on the experimental verification that has been achieved after the last review [I-8].

I-2. ANALYTICAL DEVELOPMENT

A. Sound Source Intensities

Ffowcs-Williams [I-5] has shown that, where turbulent jet convection speeds are in excess of the ambient speed of sound

$$(M_c = \frac{U_c}{a_o} > 1),$$

a pronounced finite sound peak occurs at $\cos \theta = 1/M_c$ where θ is the angle between the line to the observer and the flow direction (see figure I.1). Since this is the direction toward which Mach waves would emanate from supersonic bodies moving at a Mach number M_c, the emission is analogous to the Mach wave emission from supersonically moving eddies, the latter behaving somewhat like solid bodies. The intensity of acoustic radiation is then determined by the "shape" of the bodies (i.e., by the density gradient through the eddy). The sound source in this case is source-like (monopole); whereas, in subsonic flow the sound source is quadrupole in nature. The sound source strength is then determined

(through suitable mathematical manipulation) by density correlations in a fixed frame of reference, thus removing the complication resulting from measurements being required in the moving frame of reference as is the case of quadrupole noise.

The far-field acoustic radiation from the shear layer of a turbulent jet is then predicted to be

$$\langle p^2 \rangle = \frac{1}{16\pi^2} \int \frac{(x_f - x)^2 (y_f - y)^2}{|\vec{x}_f - \vec{x}|^6} \{\partial \bar{u}/\partial y\}^2 \, S(\vec{x}) \, d\vec{x}, \qquad (1)$$

where

$$S(\vec{x}) = \int \left\langle \frac{\partial \rho}{\partial t}\left(\vec{x}, \; t - \frac{|\vec{x}_f - \vec{x}|}{a_o}\right) \frac{\partial \rho}{\partial t}\left(\vec{x} + \vec{\xi}, \; t - \frac{|\vec{x}_f - \vec{x} - \vec{\xi}|}{a_o}\right) \right\rangle d\vec{\xi}. \qquad (2)$$

$S(\vec{x})$ is considered here to be the acoustic source strength per unit volume of turbulence. The other terms in the equations, apart from the mean velocity gradient, are dependent upon the relative position of the observer and the sound source. The velocity gradient can be measured independently of the source integral by other standard measurements. Ffowcs-Williams writes the correlations in terms of the pressure gradients by assuming locally isotropic conditions: $\rho = (1/a^2)P$. This technique requires a knowledge of the local speed of sound in the shear layer. If, however, we can measure density fluctuations directly, this approximation and requirement is not necessary. Ffowcs-Williams also shows that the sound source integral is more properly written in a frame of reference aligned with and perpendicular to the Mach wave direction of propagation.

B. Crossed-Beam Principle

The operation of the crossed-beam technique has been described elsewhere, and will therefore be discussed only briefly here. In principle, two narrow beams of selected wavelength radiation are positioned such that they intersect at a point in the region of interest in the jet. If the beam intensity for each beam is modulated by a process

which is linearly related to the local gas density fluctuations, then the intensities can be expressed by

$$i_A = I_A \int (km_f)\, d\eta = I_A \int \rho d\eta \tag{3}$$

$$i_B = I_B \int (km_f)\, d\zeta = I_B \int \rho d\zeta, \tag{4}$$

where i_A, i_B, I_A and I_B are the fluctuating and mean signals, respectively, for each of the two beams A and B. If the two signals are cross-correlated over a sufficiently long integration time, the product mean value $\langle i_A\, i_B \rangle$ will give information concerning only the fluctuations common to each beam (i.e., in the intersection region). In this way, local information on turbulence has been obtained without the necessity of inserting physical probes into the flow field [I-6]. From a more intuitive viewpoint (see figure I.2), we might consider turbulence as consisting of discrete eddies that are slightly more or less transparent to the beams of radiation than the surroundings. As an eddy passes through a beam of radiation, the light intensity at the detector changes. When the two detector outputs are cross-correlated, only the information concerning eddies passing through the beam intersection point is retained. Signal fluctuations due to source instabilities, detector noise, etc., are normally uncorrelated, although these contributions do affect the overall signal-to-noise ratio of the system [I-9].

Cross-correlation of equations (3) and (4) gives

$$G(\vec{x}) = \frac{\langle i_A i_B \rangle}{\langle I_A \rangle \langle I_B \rangle} = \int\int \langle \rho(x, y+\eta, z, t)\ \rho(x+\xi, y, z, t+\tau) \rangle\, d\eta\, d\xi, \tag{5}$$

where i_A and i_B are correlated with an arbitrary time delay τ between signals and ξ is a displacement of beam B relative to beam A in the direction of U_c. This equation expresses the correlation between two line integrals. If we can write equation (5) as

$$G(\vec{x}) = \int\int \langle \rho(x, y, z, t)\ \rho(x+\xi, y+\eta, z+\zeta, t+\tau) \rangle\, d\eta\, d\zeta \tag{6}$$

or

$$G(\vec{x}) = \underset{\text{point}}{<\rho(x,y,z,t)} \underset{\text{area}}{\int\int <\rho(x+\xi, y+\eta, z+\zeta, t+\tau)\ d\eta\ d\zeta>}, \qquad (7)$$

then, we are dealing with the correlation between the area integral of points in a plane ($x + \xi$ = constant) with an outside point (x,y,z). Such a cross-correlation has been assigned the term "point-area correlation," and is the type occurring in equation (1).

If the turbulent flow is everywhere homogeneous, then the point-area formulation is obviously proper. If departures from homogeneity are pure odd functions of space coordinates about the point (x,y,z), then these departures tend to integrate out and the point-area concept is still valid. In any event, the final proof of the point-area correlation assumption can come only from experiment. Two tests for this proof, discussed in detail in reference I-8, are summarized here.

(1) The spatial resolution of the measurements across streamlines should be limited only by the outside "point" which, in practice, is the optical beam diameter.

(2) Since the cross-correlation of signals i_A and i_B will correspond only to contributions from turbulent fluctuations normal to the beam plane, the energy spectrum should approximate the three-dimensional spectrum of turbulence. This is in contrast to a two-point hot wire measurement of the so-called one-dimensional spectrum which contains contributions due to cross-flow components. As a result, the energy spectrum for crossed-beam data should approach a -11/3 variation in the high frequency portion.

Therefore, assuming the validity of the point-area correlation approximation, equation (7) in abbreviated fashion becomes

$$G(\vec{x}) = \int\int <\rho(\vec{x}, t)\ \rho(\vec{x} + \vec{\xi},\ t + \tau)>\, d\eta\ d\zeta. \qquad (8)$$

C. Application to Sound Source Intensity Measurements

The similarity between equation (1) and equation (8) is striking. It would appear that only one further integration (point-area to point-volume) is required to obtain the sound source intensity. There are, however, two main points to be considered carefully in making the comparison. They are as follows:

(1) The radiation extinction process must be directly gas-density dependent.

(2) Time derivative and not space derivative correlations are required, and the correct retarded time difference must be used.

We will now consider these two points in greater detail.

1. Extinction Process

Several extinction processes have been used in crossed-beam studies in the past. These include scattering from natural and artificial tracers and the use of the absorption of air in the ultra-violet portion of the spectrum (Schumann-Runge bands of oxygen). Each of these has proven to be unacceptable for sound source measurements although they are useful in other turbulence parameter studies. More recently, instrumentation has been developed to measure absorption by naturally occurring CO_2 in air using the near infrared portion of spectrum. The fundamental vibration band of CO_2 near 4.3 microns is the most promising due to the absence of water vapor absorption in this region. Only naturally occurring CO_2 can be used, since only then will the optical fluctuations measured be truly representative of the gas density fluctuations in the jet. The use of the infrared spectrum also reduces the contributions to the signal fluctuations from ever present particle contaminants in the flow.

The extinction process in general can be written as

$$i + I = I_o \exp\left[-\int (\bar{\rho} + \rho) d\ell\right]$$

$$= I_o \exp\left[-\int \bar{\rho}\, d\ell\right] \exp\left[-\int \rho\, d\ell\right]$$

$$= I \exp\left[-\int \rho\, d\ell\right] .$$

Now, for small perturbations

$$\exp\left[-\int \rho \, d\ell\right] \cong 1 - \int \rho \, d\ell.$$

Thus,

$$i = -I \int \rho \, d\ell.$$

This was the form presented in a previous section.

It should be repeated at this point that ρ is analogous to km_f. This means that a comprehensive study must be made using a unique absorption calibration cell to determine the dependence of k on the static and dynamic pressure and static temperature. Therefore, knowing $\partial k/\partial P$ and $\partial k/\partial T$, the experimenter can choose the optimum wavelength and bandpass settings in the absorption band to discriminate against the temperature dependence of k. These experiments can be made only in a controlled environment free of a contribution due to scattering to the observed signal.

In principle then, it is feasible to use infrared absorption by naturally occurring CO_2 for the measurement of gas-density fluctuations. The preliminary results are given in the next section.

2. Time Derivative Requirements and Retarded Time Effects

The point-area correlation in equation (6) must be in terms of the time derivatives of the gas-density fluctuations in order to obtain an experimentally accessible form of equations (1).

For stationary time series, the correlation of time derivatives is identical with the time lag differentiation of the correlation.

$$-\left\langle \frac{\partial \rho(\vec{x},t)}{\partial t} \frac{\partial \rho(\vec{x}+\vec{\xi},\ t+\tau)}{\partial t} \right\rangle = \frac{\partial^2 \langle \rho(\vec{x},t)\ \rho(\vec{x}+\vec{\xi},\ t+\tau)\rangle}{\partial \tau^2} \tag{9}$$

$$\frac{\partial^2 G(\vec{x})}{\partial \tau^2} = \int\int \frac{\partial^2 \langle \rho(\vec{x},t)\ \rho(\vec{x}+\vec{\xi},\ t+\tau)\rangle}{\partial \tau^2} \, d\xi_2 \, d\xi_3 \tag{10}$$

$$S(\vec{x}) = \int \frac{\partial^2 G(\vec{x})}{\partial \tau^2} \, d\xi_1. \tag{11}$$

We can also simplify the retarded times in equation (1) by the approximation

$$|\vec{x}_f - \vec{x}| - |\vec{x}_f - \vec{x} - \vec{\xi}| \simeq \xi_1. \tag{12}$$

The order of time lag differentiation and space integration (equation (11)) may be interchanged in the special coordinate system $\vec{\xi} = (\xi_1; \xi_2; \xi_3)$ where the planes ξ_1 = constant are parallel to the Mach wave fronts that are generated at the source point $\vec{x}$, the reason being that retarded times are constant along such planes within the far-field approximation. This type of crossed-beam orientation is possible, but does not alleviate the problem since θ is not known <u>a priori</u>.

Now, the time delay for the orientation in figure I.2 is

$$\tau = \frac{\xi_1}{a_o} = \frac{\xi}{U_c}.$$

This time delay is also precisely that which allows an eddy to move from the upstream beam to the downstream beam along a streamline in a reference frame oriented in the flow direction $\vec{\xi} = (\xi; \eta; \zeta)$. In other words, the retarded time is correct for the area near the "common" streamline, but away from the streamline τ is a function of the particular points η and ζ. In the first approximation, the contributions should cancel as in the case for cross-flow components. Therefore, we can write equations (10) and (11) as

$$\frac{\partial^2 G(\vec{x})}{\partial \tau^2} = \int\int \frac{\partial^2 \langle \rho(\vec{x}, t) \; \rho(\vec{x}+\vec{\xi}, \; t+\tau) \rangle}{\partial \tau^2} \, d\eta \, d\zeta \tag{13}$$

$$S(\vec{x}) = \int \frac{\partial^2 G(\vec{x})}{\partial \tau^2} \, d\xi \tag{14}$$

and

$$|\vec{x}_f - \vec{x}| - |\vec{x}_f - \vec{x} - \vec{\xi}| \simeq \xi. \tag{15}$$

Now, $S(\vec{x})$, being an experimentally accessible quantity under the above assumptions, sound source intensities can be measured.

I-3. EXPERIMENTAL STUDIES

The first tests* conducted with the infrared crossed-beam system were made in the shear layer at an axial location of X/D = 4 of a subsonic jet so that comparisons could be made with more standard measuring techniques. A photograph of the one-inch diameter subsonic jet facility and infrared crossed-beam system is shown in figure I.3.

The radiation sources currently in use are glowbars operating at a temperature of 1100°K (equivalent blackbody temperature). Cassegrainian optics are used to focus the radiation from the sources into the jet flow field with an image dimension of 2mm in the flow direction and 1 mm in the transverse direction. The radiation is then collected, using similar optics and refocused on the entrance slit of a McPherson Model 218 monochromator. The experimenter can then choose the center wavelength and bandpass settings desired in the 4.3 micron absorption band of CO_2. The bandwidth initially used was typically 0.08 microns. The radiation level is monitored at the exit slit of the monochromator by using LN_2 cooled Indium-Antimonide detectors. The fluctuating signals obtained are amplified and recorded for a detailed analysis. Simultaneously, the signals are reduced on-line using a PAR correlator. A computer program is available to reduce the digitized data tapes to obtain the correlations and spectra.

The cross-correlations (zero beam separation) and mean levels obtained while traversing the spectral region from 4.1 to 4.5 microns are shown in figure I.4. Both the mean level traverse and cross-correlation traverse follow the shape of the CO_2 absorption curve as expected, but cross-correlations were recorded outside the absorption band where the absorption should fall to zero. It is felt that this is due to the contribution from scattering to the total signal since the jet has contamination from oil mist due to the compressors. In this case, the

*The data presented here were kindly supplied by Dr. R. J. Damkevala of IIT Research Institute.

signal is obviously not entirely due to CO_2 absorption, and therefore some method must be devised to treat this type of problem.

If we consider the fluctuating signals of beam A and beam B to be composed of contributions due to absorption and scattering, then

$$i_A(\lambda, \ldots) = i_{A_a}(\lambda, \ldots) + i_{A_s}(\lambda_1, \ldots) \tag{16}$$

and

$$i_B(\lambda, \ldots) = i_{B_a}(\lambda, \ldots) + i_{B_s}(\lambda_1, \ldots),$$

where we have assumed that the scattering contribution is a linear continuum across the absorption band and can thus be approximated at λ_1.

The cross-correlation of the two composite signals yields

$$\begin{aligned} \langle i_A(\lambda, \ldots)\, i_B(\lambda, \ldots) \rangle &= \langle i_{A_a}(\lambda, \ldots)\, i_{B_a}(\lambda, \ldots) \rangle \\ &+ \langle i_{A_a}(\lambda, \ldots)\, i_{B_s}(\lambda_1, \ldots) \rangle + \langle i_{A_s}(\lambda_1, \ldots)\, i_{B_a}(\lambda, \ldots) \rangle \\ &+ \langle i_{A_s}(\lambda_1, \ldots)\, i_{B_s}(\lambda_1, \ldots) \rangle . \end{aligned} \tag{17}$$

Therefore, to obtain

$$\langle i_{A_a}(\lambda, \ldots)\, i_{B_a}(\lambda, \ldots) \rangle ,$$

we must know the three remaining terms on the RHS of equation (17).

By definition,

$$Q_{aa}(\lambda, \lambda) = \frac{\langle i_{A_a}(\lambda, \ldots)\, i_{B_a}(\lambda, \ldots) \rangle}{\langle I_A \rangle \langle I_B \rangle} \tag{18}$$

and

$$Q_{ss}(\lambda_1,\lambda_1) = \frac{\langle i_{A_s}(\lambda_1, \ldots)\, i_{B_s}(\lambda_1, \ldots)\rangle}{\langle I_A \rangle \langle I_B \rangle} \quad . \tag{19}$$

Also,

$$Q_{as} = (\lambda,\lambda_1) = \frac{\langle i_{A_a}(\lambda, \ldots)\, i_{B_s}(\lambda_1, \ldots)\rangle}{\langle I_A \rangle \langle I_B \rangle}$$

$$= \frac{\langle i_{A_s}(\lambda_1, \ldots)\, i_{B_a}(\lambda, \ldots)\rangle}{\langle I_A \rangle \langle I_B \rangle} \quad , \tag{20}$$

since both processes are governed by the turbulence convection and are thus well correlated. Now, setting beam A at λ_1 and beam B at λ, cross-correlating the two signals, we get

$$\frac{\langle i_A(\lambda_1, \ldots)\, i_B(\lambda, \ldots)\rangle}{\langle I_A \rangle \langle I_B \rangle} = Q_{as}(\lambda,\lambda_1) + Q_{ss}(\lambda_1,\lambda_1) \tag{21}$$

or

$$Q_{as}(\lambda,\lambda_1) = \frac{\langle i_A(\lambda_1, \ldots)\, i_B(\lambda, \ldots)\rangle}{\langle I_A \rangle \langle I_B \rangle} - Q_{ss}(\lambda_1,\lambda_1). \tag{22}$$

Finally, we can write

$$Q_{aa}(\lambda,\lambda) = \frac{\langle i_A(\lambda, \ldots)\, i_B(\lambda, \ldots)\rangle}{\langle I_A \rangle \langle I_B \rangle}$$

$$- 2\,\frac{\langle i_A(\lambda_1, \ldots)\, i_B(\lambda, \ldots)\rangle}{\langle I_A \rangle \langle I_B \rangle}$$

$$+ Q_{ss}(\lambda_1,\lambda_1), \tag{23}$$

which is the contribution due to absorption only (see figure I.4).

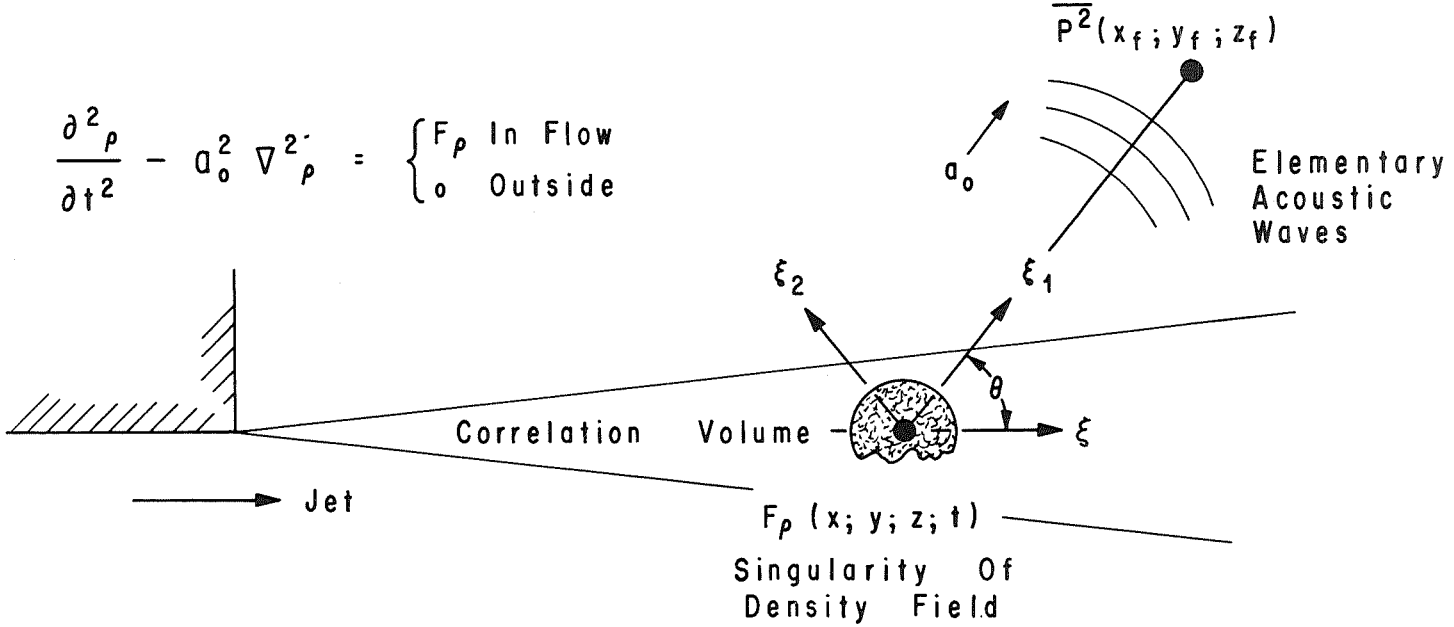
Figure I.5 shows a radial profile measured at a center wavelength of $\lambda = 4.24$ microns. The resolution of the crossed-beam system may be assessed by comparing the width of this intensity peak with the shear layer width. The consistent variation of the two-beam product mean value is evidence of resolution capabilities, and supports the earlier contention of the validity of the point-area correlation concept.

Fourier transforms performed on the cross-correlations are presented in figure I.6. Once again the point-area concept appears to be supported by experimental evidence, since the high frequency portion of the spectrum does approximate the -11/3 power law very well.

I-4. CONCLUSIONS AND FUTURE PLANS

The very promising first results presented in this paper have given confidence that the crossed-beam technique will allow measurements of sound source intensities to be made in jet flows. Toward that end, experiments are being initiated to measure two-beam correlations in a heated subsonic jet, and measurements have already begun in a specially designed absorption calibration cell to verify analytical predictions, with regard to understanding pressure and temperature effects. These measurements are to be made by varying the absorber mass, static and dynamic pressure and static temperature independently.

With this information and the already proven ability to obtain remotely point-area correlations that are not accessible to probe instruments, the crossed-beam system will have the potential of locating and measuring, for the first time, the turbulent sound source intensities in jet flows. Such measurements, taken without disturbing the flow, will not only lend support to analytical predictions, but also aid in the design and evaluation of noise suppression devices.



Far Field Sound Source Intensities

$$F(\vec{x}) = \int \langle F_\rho(\vec{x}; t)\, F_\rho(\vec{x} + \vec{\xi}; t - \frac{\xi_1}{a_o}) \rangle \, d\vec{\xi} = \text{Integration Over } \xi_1$$

Of The Time Lag Derivatives Of $\langle \rho(\vec{x}, t) \int \rho(\vec{x} + \vec{\xi}, t - \frac{\xi_1}{a_o})\, d\xi_2\, d\xi_3 \rangle$

Point Area

Product Mean Value Of Gas Density Fluctuations

FIGURE I.1. EXTENSION OF ACOUSTIC WAVES INTO FLOW

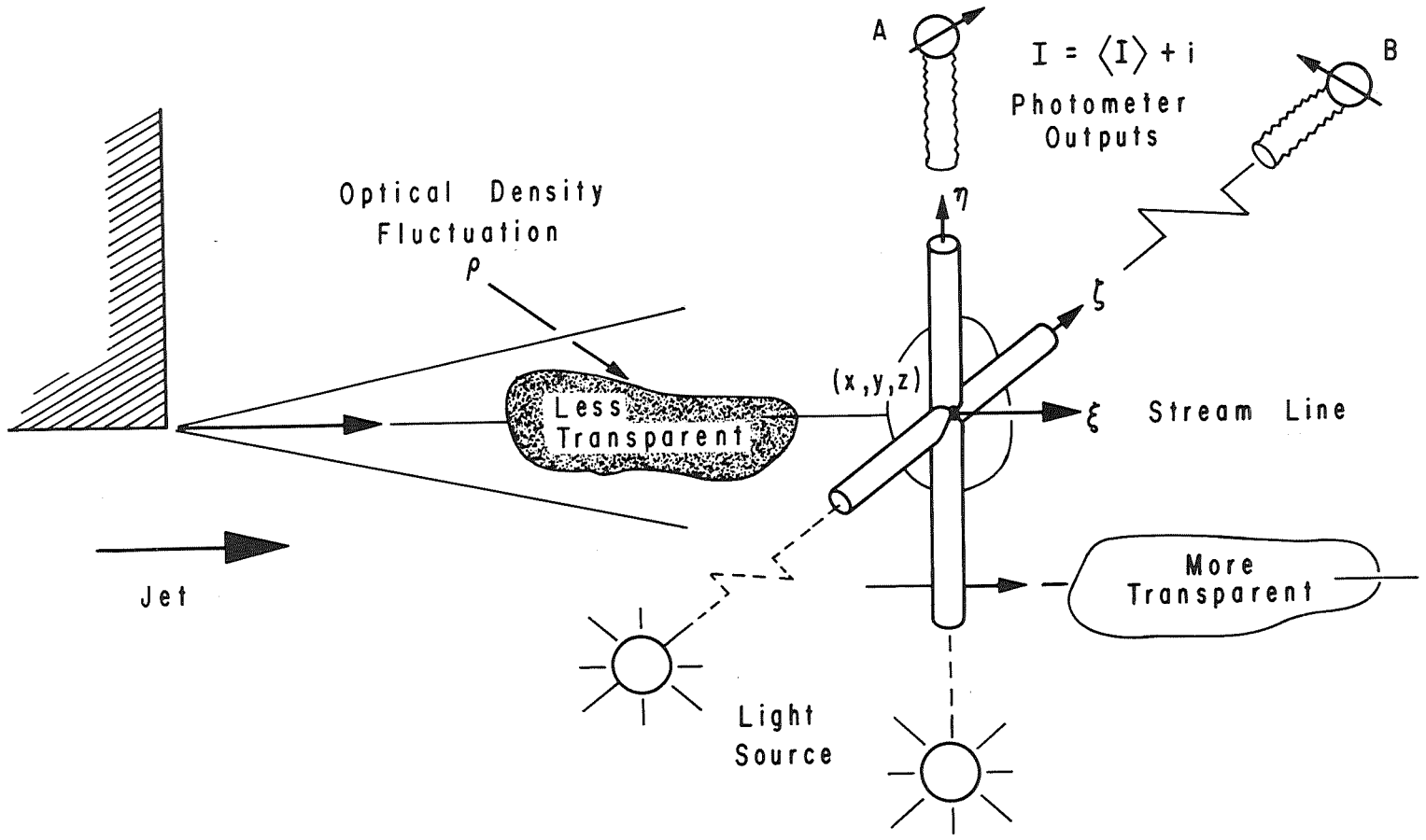


FIGURE I.2. CROSS-BEAM APPROXIMATIONS OF LOCAL SOUND SOURCE INTENSITIES

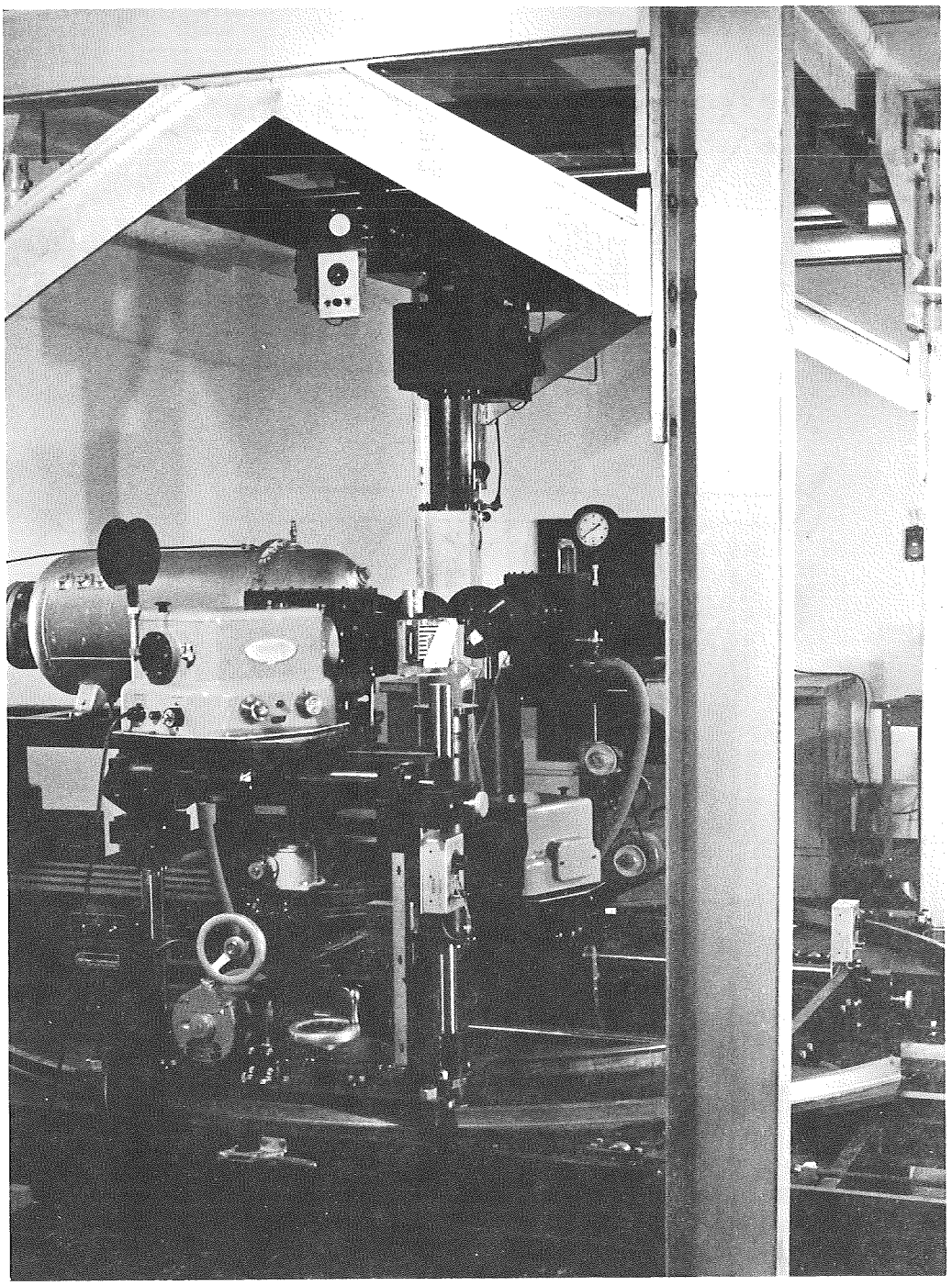


FIGURE I.3. IR X-BEAM FRAME

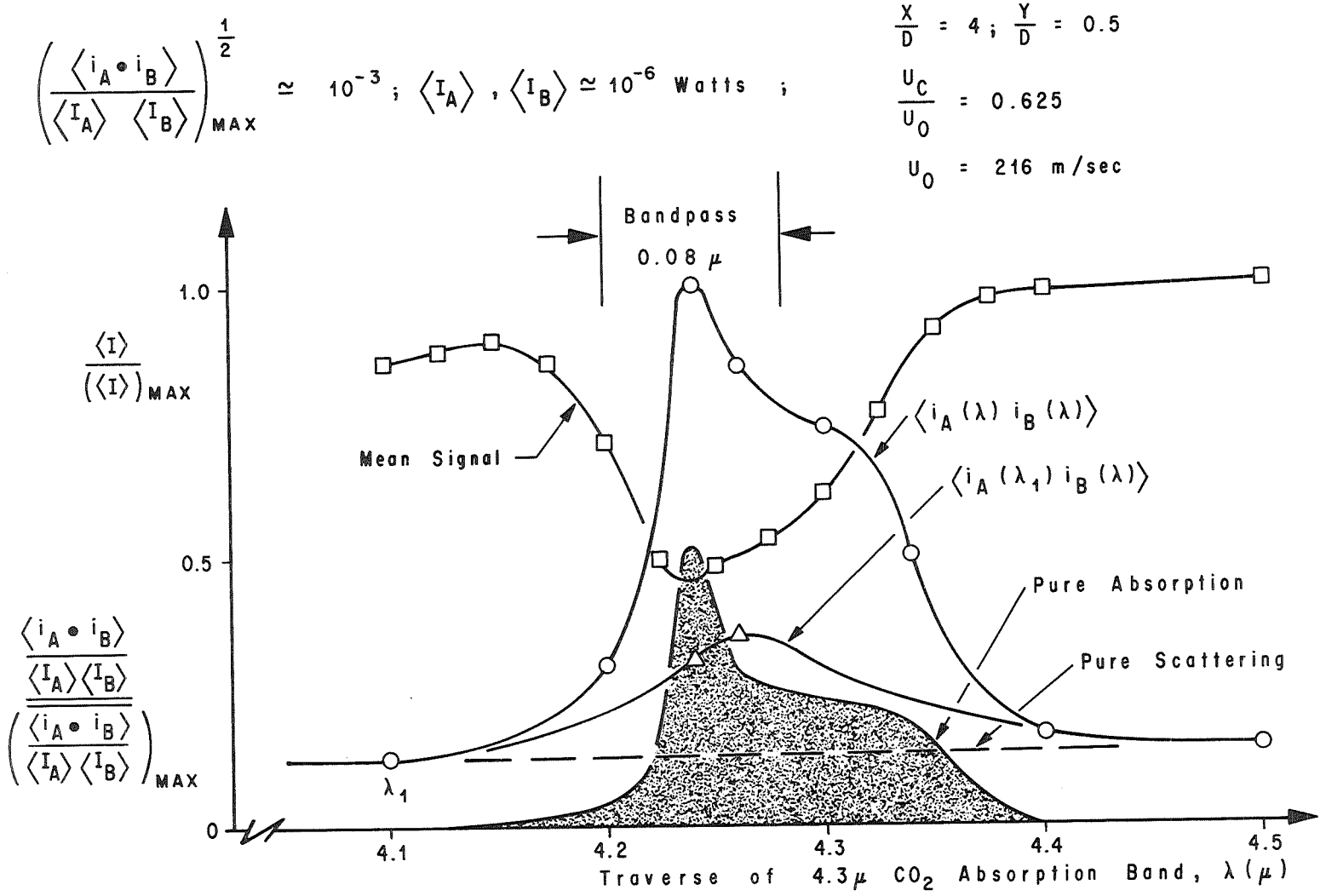

$\left(\frac{\langle i_A \cdot i_B \rangle}{\langle I_A \rangle \langle I_B \rangle}\right)^{\frac{1}{2}}_{MAX} \simeq 10^{-3}$; $\langle I_A \rangle$, $\langle I_B \rangle \simeq 10^{-6}$ Watts ;
$\frac{X}{D} = 4$; $\frac{Y}{D} = 0.5$
$\frac{U_C}{U_0} = 0.625$
$U_0 = 216$ m/sec
Bandpass
0.08 μ
1.0
0.5
0
$\frac{\langle I \rangle}{(\langle I \rangle)_{MAX}}$
$\frac{\frac{\langle i_A \cdot i_B \rangle}{\langle I_A \rangle \langle I_B \rangle}}{\left(\frac{\langle i_A \cdot i_B \rangle}{\langle I_A \rangle \langle I_B \rangle}\right)_{MAX}}$
Mean Signal
$\langle i_A(\lambda)\, i_B(\lambda) \rangle$
$\langle i_A(\lambda_1)\, i_B(\lambda) \rangle$
Pure Absorption
Pure Scattering
λ_1
4.1
4.2
4.3
4.4
4.5
Traverse of 4.3μ CO_2 Absorption Band, λ(μ)

FIGURE I.4. DECOUPLING OF ABSORPTION AND SCATTERING

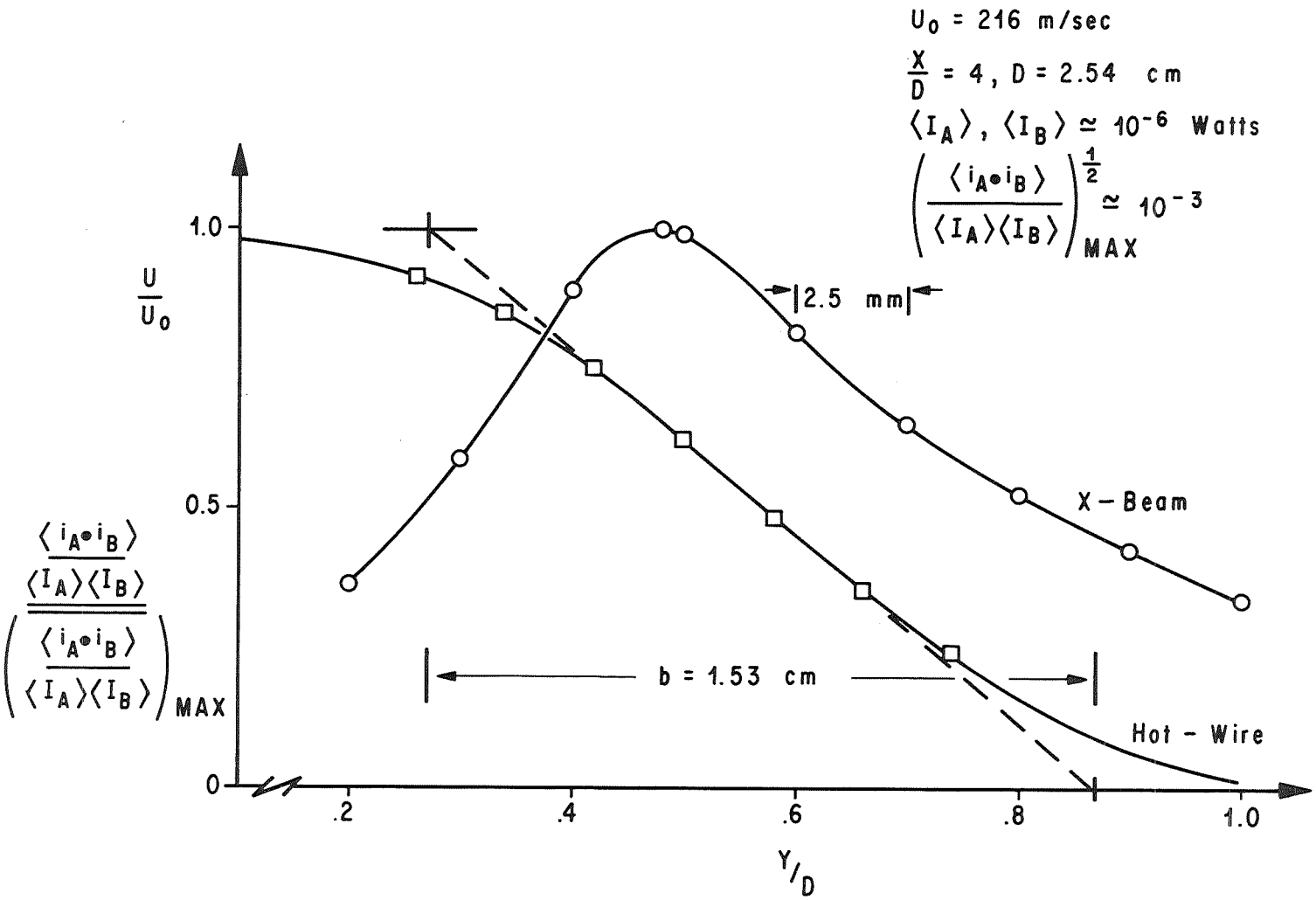


FIGURE I.5. RADIAL PROFILE OF CROSSED BEAM INTENSITY

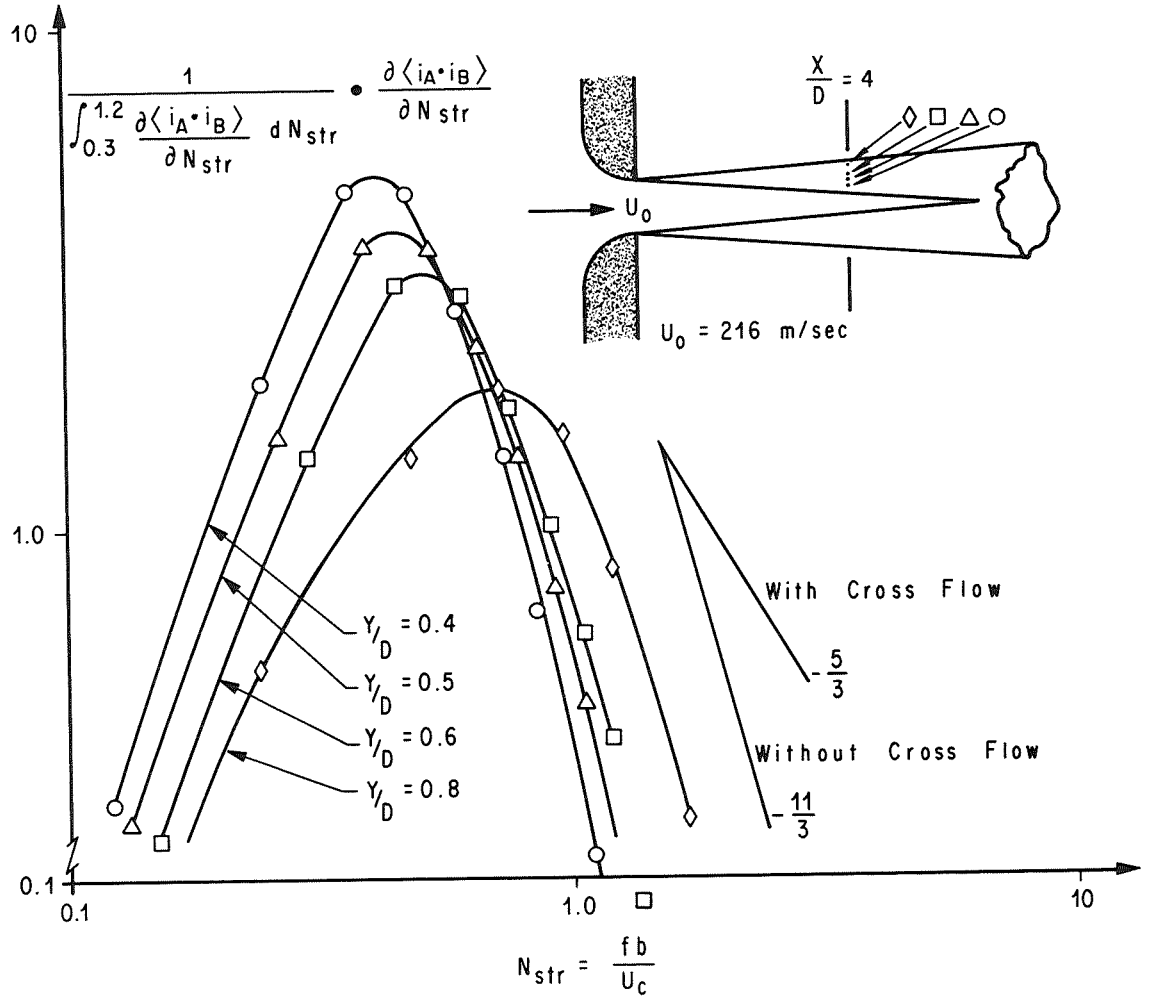


FIGURE I.6. CROSSED BEAM APPROXIMATIONS OF THREE-DIMENSIONAL SPECTRUM FUNCTIONS

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